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K. Zimmermann/ I. Zeidis

Locomotion Based on Isotropic Friction

In [1, 2], the dynamics of a system of two bodies joined by a linear elastic element was studied. The motion was excited by a harmonic force acting between the bodies. In this paper we consider the rectilinear motion along a rough plane of two identical bodies of mass M connected by a spring of stiffness c (Fig. 1, left). To each of the bodies an unbalance vibration exciter is attached. Both rotors have the same mass m and the same distance l between the center of mass and the axis of rotation. Let x_1 and x_2 denote the coordinates measuring the displacements of the constituent bodies of the system. We assume isotropic Coulomb's dry friction with coefficient k to act between the supporting plane and the bodies. The system is driven by the vibration exciters that rotate synchronously at the same angular velocity ω in the same direction with a phase shift of φ_0.

Fig.1. Model (left) and the prototype (right) of the vibration driven system

We use the dimensionless variables and parameters (labeled with the asterisk): $(x_1, x_2) = (x_1^*, x_2^*)/l$, $t = t^*\omega_0$, $\omega_0^{\,2} = c/(m+M)$, $\nu = \omega/\omega_0$, $\varepsilon = (m+M)k\,g/(l\,c)$, $\alpha = m\,c\,l/((m+M)^2 g)$, $\beta = \alpha/k$. We assume that $\varepsilon << 1$. Introduce new variables: the velocity of the center of mass, $V = (\dot{x}_1 + \dot{x}_2)/2$, and the deviation of the bodies from their common center of mass, $z = (x_2 - x_1)/2 = a\cos\varphi$. To investigate the motion of the system in the neighborhood of the main resonance, we assume $\nu = \sqrt{2} + \varepsilon\,\Delta$, where Δ is a constant quantity that has an order of unity. We are interested in the velocity-periodic steady-state motion of the system as a whole. The steady-state solution of the averaged equations of motion, corresponding to constant V, can serve as an acceptable approximate model for the steady-state motion of the basic system. Accordingly, the velocity corresponding to this solution can be used as an approximation to the average velocity of the basic system. Introduce the variables $u = V/\left(a\sqrt{2}\right)$ and $\gamma = \sin(\varphi_0/2)$ we obtain the system of algebraic equations for the steady-state solution (the velocity V and the amplitude a are constants).

$$\begin{gathered}\frac{\pi^2 \arcsin^2 u}{4\pi^2\left(1-u^2\right)} + \frac{4k^2\left[2\left(1-u^2\right) - \arcsin\, u\left(\arcsin\, u - u\sqrt{1-u^2}\right)\right]^2}{4\pi^2\left(1-u^2\right)} = (\gamma\alpha)^2 \\ a = \frac{1}{\Delta}\cdot\frac{1}{\pi\sqrt{2\left(1-u^2\right)}}\left\{\frac{\pi}{2k}\arcsin u - \frac{2k}{\pi}\left[\left(2+u^2\right)\left(1-u^2\right)\arcsin u + 2u\left(1-u^2\right)\sqrt{1-u^2} - ars\sin^3 u\right]\right\}\end{gathered} \quad (1)$$

Let (u_0, a_0) be a solution of the system of equations (1) for a given set of parameters $(\gamma, \alpha, k, \Delta)$. Then $(-u_0, a_0)$ is a solution for the set of parameters $(\gamma, \alpha, k, -\Delta)$. Hence, one can control the direction of motion of the system by changing the resonant detuning Δ in sign. For the experimental model (Fig.1, right), the dimensionless $V = \sqrt{2}\,u\,a$ found from system (1) is approximately equal to 0.17. From the numerical solution of the exact equation it follows that the average velocity of the steady-state motion of the system is close 0.2. The dimensional value is $V \approx 0.08\, m/s$.

For a system of two bodies connected by a linear spring and excited by unbalanced rotors, the direction of motion can be reversed by changing the difference between the natural frequency of the system and the angular velocities of the rotors in sign. The change in the direction of rotation of the rotors is not required. The magnitude of the velocity of the motion can be controlled by changing the phase shift between the rotations of the rotors.

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[1] Zimmermann K., Zeidis I.: Worm-like locomotion as a problem of nonlinear dynamics. *J. of Theor. and Appl. Mech.* **45**:179–187, 2007

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